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Role prioritization of hydrogen production technologies for promoting hydrogen economy in the current state of China

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ABSTRACT

Hydrogen production technologies play an important role in the hydrogen economy of China. However, the roles of different technologies played in promoting the development of hydrogen economy are different. The role prioritization of various hydrogen production technologies is of vital importance for the stakeholders/decision-makers to plan the development of hydrogen economy in China and to allocate the finite R&D budget reasonably. In this study, DPSIR framework was firstly used to identify the key factors concerning the priorities of various hydrogen production technologies; then, a fuzzy group decision-making method by incorporating fuzzy AHP and fuzzy TOPSIS was proposed to prioritize the roles of different technologies. The proposed method is capable of allowing multiple groups of stakeholders/decision-makers to participate in the decision-making and addressing problems with uncertainty and imprecise information. The prioritization results by using the proposed method demonstrated that the technologies of coal gasification with CO_2 capture and storage and hydropower-based water electrolysis were regarded as the two most important hydrogen production pathways for promoting the development of hydrogen economy in China among the five assessed technologies.

Contents

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1. Introduction

The total number of automotive vehicles in China is forecasted to reach 300 millions units in 2050; and the corresponding increase in the consumption of fossil fuel could lead to serious environmental problems [1]. Hydrogen fuel cell vehicles are regarded as a promising alternative to solve the severe energy and environmental problems caused by the excessive use of fossil fuel for transportations [2,3]. Accordingly, China is making great effort to promote the exploitation and application of hydrogen energy with the aim of not only satisfying the hydrogen demand of the conventional chemical industry, but also achieving successful transition to hydrogen economy [4].

China is the world‘s largest hydrogen consumer, accounting for about 22% of the total amount of world's total hydrogen consumption [5]. Ma et al. [6] estimated that the total demand of hydrogen in China is between 25.110 and 70.5376 Mtce in 2050. In China, hydrogen is mainly used in two areas: the conventional chemical industry (i.e. the production of ammonia and methanol) and commercial purpose (i.e. hydrogen fuel cell vehicles and food processing). It was estimated that around 12.42 million tons hydrogen was produced on-site for the conventional chemical industry in 2007, among which, 57.3% was from coal, 23.0% was from natural gas, and 19.7% was from oil. Form the aspect of application, 75.8% was used as feedstock for the production of ammonia, 10.5% was for the production of methanol, 13.7% was for oil refining, respectively [7]. Compared to the conventional chemical industry, the amount of hydrogen used for the commercial purpose is very small, merely 5% of the total produced hydrogen [7].

Hydrogen production is the key step for hydrogen economy since hydrogen is an energy carrier similar to electricity that must be produced from the primary energy resources [8]. Many methods can be used for hydrogen production e.g. biomass gasification [9–13], steam methane reforming [14–16], coal gasification [17–20], biological technologies [21–23], water electrolysis [24–26], and other new emerging technologies such as thermochemical cycles by solar energy [27], supercritical water gasification of biomass [28] and photoelectrolysis [29]. In China, the majority of the hydrogen is produced by coal gasification, reforming of natural gas and oil, and water electrolysis. The new emerging alternative approaches by using renewable resources as feedstock (i.e. biomass gasification and biomass pyrolysis) or by combining with some other renewable or low-carbon energies for hydrogen production (i.e. solar power based electrolysis of water and nuclear-based high temperature electrolysis) are still under the pilot stage [30].

According to the above analysis, it is obvious that hydrogen economy in China is still under the infant stage although China's administration has made significant effort on promoting the development of hydrogen economy. China is a developing country, and economic performance is usually the first target to be considered for any market behaviors. At present, the cost of hydrogen is still high in China, which has a significant negative effect on the hydrogen economy in China, especially on the consumers' acceptability. Han et al. [31] pointed out that the current high cost of hydrogen for fuel cell vehicles is one of the necessaries that need to be resolved for the successful commercialization of hydrogen fuel cell vehicles in China. Yao et al. [4] estimated that the cost for hydrogen production by coal gasification, natural gas steam reforming, and water electrolysis is 8.34 Yuan/kg, 6.82 Yuan/kg, and 12.16 Yuan/kg, respectively. Feng et al. [1] investigated the life cycle cost of hydrogen for fuel cell vehicles in Beijing, and the two scenarios, i.e. methanol reforming onboard and coal gasification (hydrogen gas cylinder by truck), were regarded as the best plans with the cost of 14.68 Yuan RMB/kg and 14.74 Yuan RMB/kg, respectively. As for the economic performance of hydrogen based on new emerging alternative technologies, Liu et al. [30] estimated that the cost of hydrogen by the first solar-hydrogen system is 96.6 Yuan RMB/Nm^3. Lv et al. [32] reported that the cost of hydrogen based on the biomass gasification is only around 1.22 Yuan RMB/Nm^3. It is obvious that different hydrogen production pathways have different economic performances. Similarly, they also have different performances on environmental issues, technological concerns, social–political aspects, etc. Therefore, the priorities and roles of the various hydrogen production technologies to China's stakeholders/decision-makers are different. It is of vital importance to provide a reliable method for assessing and prioritizing various hydrogen production technologies that the stakeholders/decision-makers can employ to plan the development of hydrogen economy in China and to allocate the finite R&D budget reasonably.

The assessment and prioritization of hydrogen production technologies has to incorporate various evaluation criteria concerning different aspects, i.e. technical, economic, environmental, and social–political aspects. Accordingly, it is a typical multi-criteria decision-making (MCDM) problem and has been studied in a variety of literatures. Ren et al. [33] developed a fuzzy multi-actor multi-criteria decision making method for sustainability assessment of biomass-based technologies for hydrogen production. Manzardo et al. [34] developed a grey-based group decision-making methodology for selecting the most sustainable hydrogen production technologies in the life cycle perspective. McDoWall and Eames [35] used an expert-stakeholder multi-criteria mapping approach to assess the environmental, social and economic sustainability of six possible hydrogen energy systems for UK. Pilavachi et al. [36] used an analytical hierarchy process to evaluate various hydrogen production methods. Heo et al. [37] and Lee et al. [38] used fuzzy analytical hierarchy processes to assess the different hydrogen production methods. Chang et al. [39] adopted a fuzzy Delphi method for evaluating the different hydrogen production technologies. Lee et al. [40] developed a hybrid multi-criteria decision-making method by integrating the analytical hierarchy process and data envelopment analysis to measure the relative efficiency of hydrogen energy technologies. These studies are helpful for the stakeholders/decision-makers to have a better understanding of different hydrogen production technologies and to select the most sustainable or the most preferred hydrogen production technologies, and thus all these methodologies can be referred for prioritizing the roles of different hydrogen production technologies for promoting the development of hydrogen economy in China. However, an improved method that can address two problems is more preferred. First, the improved method is expected to be capable of determining the criteria system for the assessment of various technologies based on the real requests of the stakeholders/decision-makers. Second, the ability of the methodology for addressing uncertainties, imprecision and group decision-making has to be realized for the practical assessment and role prioritization.

As for the criteria system, it is essential and prerequisite for the successful prioritization to establish a complete criteria system, which significantly affects the accuracy of the assessment [41,42]. The criteria system for the assessment of hydrogen production technologies has been studied in many literatures. However, the criteria established in these studies cannot be used directly, because the purpose of this study is to prioritize the different hydrogen production technologies for planning the development of hydrogen economy in China. Accordingly, the criteria should consider not only the current status of hydrogen economy in China, but also China's actual conditions and the preferences/willingness of the stakeholders. Therefore, the criteria system in this study should be object-oriented, which requires a methodology that can aid the stakeholders/decision-makers to identify the key criteria for assessing various technologies.

Due to the availability and uncertainty of the relative information as well as the vagueness of human's feeling and recognition, the judgment of the decision makers is usually difficult to be directly represented by crisp numbers, and it is also difficult for the stakeholder/decision-makers to evaluate the performance of some criteria by using exact numerical values [42,43]. They rather use linguistic terms to address the criteria and the weights of the criteria subjectively.

Fuzzy set theory has the ability to address the problems under uncertainties and imprecision by transferring vagueness provided by linguistic values to quantification represented by crisp numbers [43]. When solving the multi-criteria decision making problems under uncertainties and imprecision, it is usually combined with the multi-criteria decision making methods such as technique for order preference by similarity to ideal solution (TOPSIS) [44] and analytic hierarchy process (AHP). Various fuzzy extensions of TOPSIS and AHP have been developed by combining fuzzy set theory in the literatures [45–50] to address the linguistic assessments in the multi-criteria decision making problems with retaining the thoughts of the conventional TOPSIS and AHP.

Besides uncertainty and imprecision, many important decision-making problems have to deal with group decisions, i.e. decisions made by organizations or certain groups [51]. Prioritizing the hydrogen production technologies is one of the most significant tasks for hydrogen development in regional or national levels, and multiple actors, organizations and groups should be invited to participate in the decision-making. Therefore, it is urgent that the developed methodology for prioritizing the hydrogen production technologies is able to allow group stakeholders/decision-makers to participate in the process.

In this paper, ten criteria regarding the four aspects of the hydrogen production technologies in China were firstly obtained based on Drivers–Pressures–State–Impact–Response analysis. Subsequently, a novel methodology by combining fuzzy AHP and fuzzy TOPSIS was proposed for prioritizing the hydrogen production technologies, which enables group stakeholders/decision-makers to participate in the process of decision-making and is capable of addressing uncertainty and imprecision by allowing stakeholders/decision-makers to use linguistic terms for describing the importance of the criteria and the performance of the alternatives with respect to each criterion

2. Criteria system for assessing the hydrogen production technologies

In this section, an object-oriented method by integrating Drivers–Pressures–State–Impact–Response (DPSIR) analysis framework was employed for determining the criteria for the prioritization of a variety of hydrogen production technologies in China.

2.1. DPSIR framework

The framework of DPSIR analysis was developed by the Organization of Economic CO-operation and Development for gathering information in an analytical and causal way, which is able to differentiate the causes, effects as well as human measures and responses that control the impacts to the end users [52,53]. It is a method derived from Pressure–State–Response (PSR) and Diver–State–Response (DSR) [54,55] that can help decision-making by structuring and organizing indicators to various decision-makers [56,57]. DPSIR framework was originally developed for environmental reporting purposes by investigating the cause–effect relationships between environmental and human systems [58]. Recently, it has been widely used in several other fields, e.g. water resources [59] and transportation network [60]. In this study, it was used to analyze the cause–effect relationships in the hydrogen economy of China with the aim to identify the key factors concerning the priorities of the various hydrogen production technologies in China.

As illustrated in Fig. 1, DPSIR framework consists of five components, i.e. Drivers, Pressures, State, Impact and Responses [58,61].

- *Drivers* are the underlying causes. Therefore, they refer to the reasons for developing hydrogen production technologies in China, e.g. the social, economic and environmental benefits by developing hydrogen production technologies. Two typical examples are the increase of hydrogen fuel cell vehicles demands and energy security.
- *Pressures* are the consequences of the drivers. The pressures mainly refer to the negative impacts on environmental, social and technical aspects caused by the divers. For instance, the increase of fuel cell vehicles could cause the shortage of hydrogen supply and environmental contaminations.
- *State* represents the status of hydrogen economy with respect to economic, environmental, social and technical aspects affected by the pressures. For example, the shortage of hydrogen is an indictor reflecting the incompletion of hydrogen infrastructures, which, therefore, can be regarded as an indicator to depict the state of hydrogen economy in China.
- *Impact* refers to the macro-effects on economic, environmental, social and technical aspects by changing the current state of hydrogen economy in China.
- *Responses* demonstrates the actions implemented by the society (stakeholders/decision-makers) to prevent, eliminate or compensate the negative impacts, such as policies, regulations and plans.

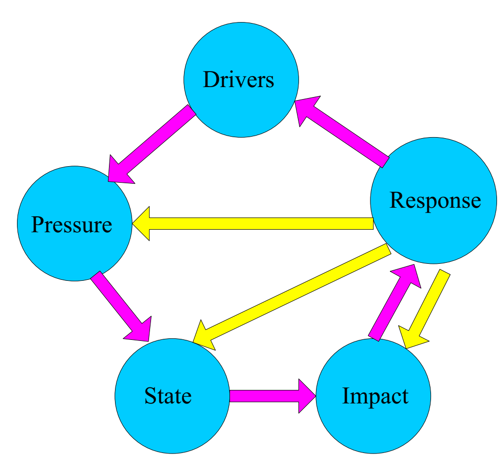

Fig. 1. Schema drawing of DPSIR analysis.

2.2. Method for criteria identification

The criteria identification by integrating DISIR framework is composed of three main steps: DPSIR analysis of hydrogen economy in China, factor transformation, and criterion screening.

Step 1: DPSIR analysis of Hydrogen economy in China. In this step, the representative stakeholders/decision-makers/experts, e.g. as senior engineers from hydrogen industry, experts from the government-funded research institutes, professors whose expertise is hydrogen energy, administrative executors from the energy sector, drivers of hydrogen fuel cell vehicles, were invited to attend a colluquisium for discussing and analyzing the hydrogen economy in China using DPSIR framework. In the colluquisium, statistics, reports, books and papers were provide to the participants; and the objective of this colluquisium and the principle of DPSIR framework were presented to them in detail. Subsequently, they were asked to think about the "Drivers" in hydrogen economy of China, and then to determine the "Pressures", "State", "Impact" and "Responses" according to the

Fig. 2. DPSIR framework of the hydrogen economy in China.

Table 1
Criterion system for the assessment of hydrogen production technologies.

Aspect	Criteria	Abbreviation	Reference
Technical (T)	Technology maturity	C_1	[33]
	Technology reliability & stability	C_2	[33]
	Feedstock renewability	C_3	Defined in this study
Economic (EC)	Cost per unit of H_2	C_4	[36]
	Market share	C_5	[33]
	Contribution to GDP	C_6	Defined in this study
Environmental (EN)	Contribution to GHG mitigation	C_7	[33]
Social–political (SP)	Contribution to energy security	C_8	Defined in this study
	Social acceptability	C_9	[33]
	Degree of government support	C_{10}	Defined in this study

cause–effect relationships existing in the hydrogen economy of China. The organizer recorded the results and drew the DPSIR framework of the hydrogen economy in China according to the results.

Step 2: Factor transformation. In this step, the factors in "Drivers", "Pressures", "State", "Impact" and "Responses" were transformed into criteria in four aspects, i.e. economic, environmental, technical and social–political aspects. For instance, the factor "energy security" in "Drivers" could be transformed into the criterion of "contribution for energy security" belonging to political–social aspect. The purpose of this step is to determine all the criteria concerning the development of hydrogen economy in China.

Step 3: Criterion screening. The purpose of this step is to screen the independent criteria related to the assessment of hydrogen production technologies as some interactions may exist between the factors determined in step 2. Moreover, some factors concerning hydrogen storage, hydrogen transportation and hydrogen applications, which have little relationships with the hydrogen production, may be incorporated in step 2. Thus, it is necessary to screen the criteria according to the actual conditions.

2.3. Criteria system

By completing the three steps of the DPSIR framework of the hydrogen economy in China (as shown in Fig. 2), the criteria system for the prioritization of hydrogen production technologies in China was determined in Table 1, which includes 10 criteria in 4 aspects.

2.3.1. Economic aspect

There are three criteria in the economic aspect, i.e. cost per unit of H_2, market share, and contribution to Gross Domestic Production (GDP).

(1) *Cost per unit of H_2*. It represents the total cost including capital cost, operation and maintenance cost, feedstock cost, and production cost for producing a unit of H_2.
(2) *Market share*. It is a measure of the potential sales of the hydrogen produced by each technology.
(3) *Contribution to GDP*. It is a criterion to measure the effect of each hydrogen production technology on promoting the economic development of the local region.

2.3.2. Environmental aspect

Contribution to Greenhouse gas (GHG) mitigation is the only criterion in the environmental aspect.

(1) Contribution to GHG mitigation. It is a measure of the effect of different hydrogen production technologies for providing hydrogen to fuel cell vehicles on GHG mitigation comparing to the use of fossil fuels in a life cycle perspective.

2.3.3. Technical aspect

Technical aspect is composed of three criteria, i.e. technology maturity, technology reliability & stability, and feedstock renewability.

(1) *Technology maturity*. It is a measure of the maturity degree of each hydrogen production technology referring to how widespread and how proficiently that each technology could be used at both international and national levels.
(2) *Technology reliability & stability*. It is a criterion to measure the resistance and robustness of each hydrogen production technology against failure.
(3) *Feedstock renewability*. It is a measure of the renewable potential of the feedstock of each technology.

2.3.4. Social–political aspect

The social–political aspect consists of three criteria, i.e. contribution to energy security, social acceptability, and degree of government support.

(1) *Contribution to energy security*. It is a measure of the effect of each hydrogen production technology on the diversity of national energy supply. New hydrogen production technologies are usually beneficial to the diversity of national energy supply.
(2) *Social acceptability*. The concept of social acceptability is defined as the overview of the opinions on the hypothesized realization of the hydrogen production projects using different technologies by the local residents.
(3) *Degree of government support*. It is a measure of the relevance of each hydrogen production technology to the policies, regulations, law and plans drafted by the governments.

3. Methods

3.1. Fuzzy theory

Since the judgments of the stakeholders/decision-makers are usually in vague, subjective and uncertain ways, it is difficult to use crisp values to describe their preferences. At these cases, linguistic variables have to be used to deal with the problems that cannot be defined quantitatively [46,48].

Linguistic variables refer to variables whose values are defined by words or sentences in a natural or artificial language [62–64]. Each linguistic variable can be assigned one or more linguistic terms, which are in turn connected to numeric values through the mechanism of membership functions [63,64]. Fuzzy numbers are usually more adequate than real number to be used for connecting

the linguistic terms [46]. Fuzzy numbers are a fuzzy subset of real numbers, representing the expansion of the idea of the confidence interval [62]. The properties of fuzzy numbers were introduced as follows.

Definition 1. A fuzzy set, $\tilde{a}$, is in a universe of discourse X characterized by a membership function $\mu_{\tilde{a}}(x)$, which associates with each element x in X, a real number in the interval [0,1]. The function value represents the grade of membership of x in $\tilde{a}$. The triangular fuzzy number is usually used in fuzzy study, and $\tilde{a}$ can be defined by a triplet (a^L, a^M, a^U). Its conceptual mathematical and schema form are shown in Eq. (1) and Fig. 3, respectively,

$$\mu_{\tilde{a}}(x) = \begin{cases} 0 & x \le a^L \\ \frac{x-a^L}{a^M-a^L} & a^L < x \le a^M \\ \frac{x-a^U}{a^M-a^U} & a^M < x \le a^U \\ 0 & x > a^U \end{cases} \tag{1}$$

Definition 2. The operational laws of two triangular Fuzzy numbers, $\tilde{a} = (a^L, a^M, a^U)$ and $\tilde{b} = (b^L, b^M, b^U)$

$$\tilde{a} + \tilde{b} = (a^L, a^M, a^U) + (b^L, b^M, b^U) = (a^L + b^L, a^M + b^M, a^U + b^U) \tag{2}$$

$$\tilde{a} - \tilde{b} = (a^L, a^M, a^U) = (b^L, b^M, b^U) = (a^L - b^U, a^M - b^M, a^U - b^L) \tag{3}$$

$$\tilde{a} \times \tilde{b} = (a^L, a^M, a^U) \times (b^L, b^M, b^U) = (a^L \cdot b^L, a^M \cdot b^M, a^U \cdot b^U) \tag{4}$$

$$\tilde{a} / \tilde{b} = (a^L, a^M, a^U) / (b^L, b^M, b^U) = (a^L / b^U, a^M / b^M, a^U / b^L) \tag{5}$$

$$k\tilde{a} = k \times (a^L, a^M, a^U) = (ka^L, ka^M, ka^U) \tag{6}$$

$$(\tilde{a})^{-1} = (1/a^U, 1/a^M, 1/a^L) \tag{7}$$

where $a^L, a^M, a^U, b^L, b^M, b^U$ are positive herein.

Definition 3. The distance between $\tilde{a} = (a^L, a^M, a^U)$ and $\tilde{b} = (b^L, b^M, b^U)$

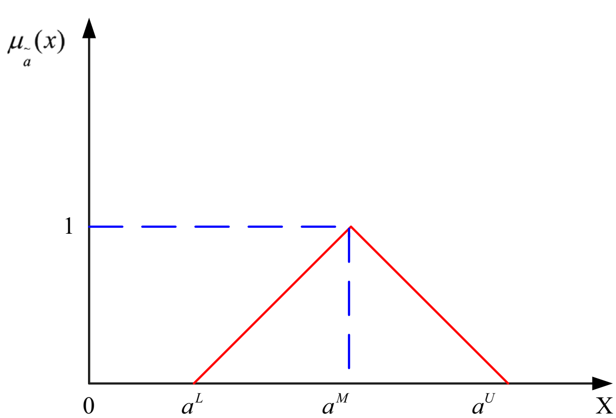

Fig. 3. Schema drawing of the triangular fuzzy number $\tilde{a} = (a^L, a^M, a^U)$.

can be determined by Eq. (8).

$$d(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}[(a^L - b^L)^2 + (a^M - b^M)^2 + (a^U - b^U)^2]} \tag{8}$$

3.2. Fuzzy group decision making method

3.2.1. Fuzzy analytic hierarchy process

Analytic hierarchy process (AHP) is a powerful tool for determining the priorities among various criteria with different importances [49]. The first step of fuzzy AHP is to determine the pair-wise comparison matrices by assigning the linguistic terms to the comparison matrix according to the relative importance of the criteria [62] (Eq. (9)).

The linguistic variables assigned in the comparison matrices can be determined according to the linguistic scale for comparison matrices, and the triangular fuzzy numbers are used to describe the linguistic scale, as shown in Table 2. The pair-wise comparison can be determined according to Table 2

$$\tilde{A} = \begin{vmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{vmatrix} = \begin{vmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{n1} & 1/\tilde{a}_{2n} & \cdots & 1 \end{vmatrix} \tag{9}$$

where

$$\tilde{a}_{ij} = \begin{cases} \tilde{1},\ \tilde{3},\ \tilde{5},\ \tilde{7},\ \tilde{9} & \text{criterion}i\text{isrelativeimportancetocriterion}j \\ 1, \quad i=j \\ \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1} & \text{criterion}j\text{isrelativeimportancetocriterion}i \end{cases}$$

According to the geometric mean technique developed by Buckley [56], the fuzzy geometric mean and fuzzy weight of each criterion can be calculated by Eqs. (10) and (11), respectively.

$$\tilde{r}_j = (\tilde{a}_{j1} \times \tilde{a}_{j2} \cdots \times \tilde{a}_{jn})^{1/n} \tag{10}$$

$$\omega_j = \tilde{r}_j \times (\tilde{r}_1 + \tilde{r}_2 + \cdots + \tilde{r}_n)^{-1} \tag{11}$$

where $\tilde{r}_j$ is the geometric mean of the fuzzy comparison values of j-th criterion to other criteria, and ω_j represents the fuzzy weight of the j-th criterion

Assuming a group of decision makers participate in the decision-making, the fuzzy comparison matrix and the weighting vector determined by the k-th decision-maker can be determined by Eqs. (12) and (13), respectively.

$$\tilde{A}^k = \begin{vmatrix} 1 & \tilde{a}^k_{12} & \cdots & \tilde{a}^k_{1n} \\ \tilde{a}^k_{21} & 1 & \cdots & \tilde{a}^k_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}^k_{n1} & \tilde{a}^k_{n2} & \cdots & 1 \end{vmatrix} \tag{12}$$

$$\tilde{W}^k = \left(\tilde{\omega}^k_1, \tilde{\omega}^k_2, \cdots, \tilde{\omega}^k_n\right) \tag{13}$$

Table 2
Linguistic scale for the comparison matrix [62].

Fuzzy number	Linguistic scales	Abbreviation	Scale of the fuzzy number
$\tilde{1}$	Equally important	EQ	(1,1,3)
$\tilde{3}$	Weakly important	WE	(1,3,5)
$\tilde{5}$	Essentially important	ES	(3,5,7)
$\tilde{7}$	Very strong important	VS	(5,7,9)
$\tilde{9}$	Absolutely important	AB	(7,9,9)
Reciprocal	Reciprocal of all above	LEQ, LWE, LES, LVS, LAB	With the reciprocal of the above

where $\tilde{\omega}_j^k$ is the weight of the j-th criterion determined by the k-th decision-maker.

3.2.2. Fuzzy TOPSIS methodology and group decision-making

In the conventional TOPSIS method, the priority sequence of the alternatives is arranged according to the idea that the best alternative should have the shortest distance to the ideal solution and the largest distance to the anti-ideal solution. The method of fuzzy TOPSIS by combining TOPSIS and fuzzy theory [47,49,63,64] is able to allow multiple decision-makers to participate in the decision-making, and therefore, has been popularized to solve the group decision-making problems. The procedure of the Fuzzy TOPSIS used in this paper can be divided into 9 steps as follows.

Step 1 Assuming that L experts or L groups of representative experts were invited to participate in the decision making, the fuzzy decision making matrix given by the k-th decision-maker can be expressed by Eq. (14).

$$\begin{array}{cccccc} & C_1 & C_2 & & C_n \\ A_1 & \tilde{x}_{11}^k & \tilde{x}_{12}^k & \cdots & \tilde{x}_{1n}^k \\ A_2 & \tilde{x}_{21}^k & \tilde{x}_{22}^k & \cdots & \tilde{x}_{2n}^k \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & \tilde{x}_{m1}^k & \tilde{x}_{m2}^k & \cdots & \tilde{x}_{mn}^k \end{array} \tag{14}$$

where $\tilde{x}_{ij}^k = (x_{ij}^{kL}, x_{ij}^{kM}, x_{ij}^{kU})$

Step 2 Using the fuzzy AHP to determine the relative importance of each criterion, the weighting coefficient of the j-th criterion determined by the k-th expert can be expressed by Eq. (15),

$$\tilde{\omega}_j^k = \left(\omega_j^{kL}, \omega_j^{kM}, \omega_j^{kU}\right) \tag{15}$$

Step 3 Normalizing the fuzzy decision making matrix by following the transformation formulas shown in Eqs. (16)–(19). The obtained normalized decision making matrix is as Eq. (20).

$$\tilde{r}_{ij}^k = \left(\frac{x_{ij}^{kL}}{x_{\max}^{kU}}, \frac{x_{ij}^{kM}}{x_{\max}^{kU}}, \frac{x_{ij}^{kU}}{x_{\max}^{kU}}\right), \quad j \in B \tag{16}$$

$$x_{\max}^{kU} = \max_i x_{ij}^{kU}, j \in B \tag{17}$$

$$\tilde{r}_{ij}^k = \left(\frac{x_{\min}^{kL}}{x_{ij}^{kU}}, \frac{x_{\min}^{kL}}{x_{ij}^{kM}}, \frac{x_{\min}^{kL}}{x_{ij}^{kL}}\right), \quad j \in C \tag{18}$$

$$x_{\min}^{kL} = \min_i x_{ij}^{kL}, j \in C \tag{19}$$

where

B={Beneficial criteria| the higher the value of the criteria, the better it would be}

C={Cost criteria| the lower the value of the criteria, the better it would be }

$$\tilde{R} = |\tilde{r}_{ij}^k|_{m \times n} \tag{20}$$

Step 4 Calculating the weighted fuzzy normalized decision making matrix by Eq. (21).

$$\tilde{V}^k = |\tilde{v}_{ij}^k|_{m \times n} = \begin{vmatrix} \tilde{\omega}_1^k \tilde{r}_{11}^k & \tilde{\omega}_2^k \tilde{r}_{12}^k & \cdots & \tilde{\omega}_n^k \tilde{r}_{1n}^k \\ \tilde{\omega}_1^k \tilde{r}_{21}^k & \tilde{\omega}_2^k \tilde{r}_{22}^k & \cdots & \tilde{\omega}_n^k \tilde{r}_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{\omega}_1^k \tilde{r}_{m1}^k & \tilde{\omega}_2^k \tilde{r}_{m2}^k & \cdots & \tilde{\omega}_n^k \tilde{r}_{mn}^k \end{vmatrix} \tag{21}$$

Step 5 Determining the fuzzy positive-ideal solution and fuzzy negative-ideal solution, according to Eqs. (22)–(25), respectively.

$$A^{k+} = \left(v_1^{k+}, v_2^{k+}, \cdots, v_n^{k+}\right) \tag{22}$$

$$v_j^{k+} = \max_i \tilde{v}_{ij}^k, j = 1, 2, \cdots, n \tag{23}$$

$$A^{k-} = \left(v_1^{k-}, v_2^{k-}, \cdots, v_n^{k-}\right) \tag{24}$$

$$v_j^{k-} = \min_i \tilde{v}_{ij}^k, j = 1, 2, \cdots, n \tag{25}$$

Step 6 Calculating the distance between each alternative to the fuzzy positive-ideal solution and fuzzy negative-ideal solution by Eqs. (26) and (27), respectively.

$$d_i^{k+} = \sum_{j=1}^n d(\tilde{v}_{ij}^k, v_j^{k+}), i = 1, 2, \cdots, m \tag{26}$$

$$d_i^{k-} = \sum_{j=1}^n d(\tilde{v}_{ij}^k, v_j^{k-}), i = 1, 2, \cdots, m \tag{27}$$

Step 7 Calculating the closeness coefficient by Eq. (28)

$$CC_i^k = \frac{d_i^{k-}}{d_i^{k+} + d_i^{k-}} \tag{28}$$

where CC_i^k is the closeness coefficient of the i-th alternative determined by the k-th expert.

Step 8 Calculating the integrated closeness coefficient according to Eq. (29).

$$CC_i = \left(\prod_{k=1}^L CC_i^k\right)^{1/L} \tag{29}$$

where CC_i is the integrated closeness coefficient of the i-th alternative.

Step 9 Ranking the order of the alternatives according to the principle that the better alternative has a larger integrated closeness coefficient.

4. Prioritization of the hydrogen production technologies

4.1. Hydrogen technologies for prioritization

There are various technologies for hydrogen production that can use different resources as the feedstock. Since the purpose of this study is to prioritize the role of various hydrogen production technologies in the development of hydrogen economy in China, the authors only considered the technologies that have the potential to produce hydrogen in large scale in order to make this study useful and meaningful for guiding hydrogen practice in China. According to the suggestions of several experts in the field of hydrogen energy, five alternative hydrogen production technologies were studied in this paper.

Scenario 1: Steam methane reforming (SMR).
Scenario 2: Coal gasification with CO_2 capture and storage (CGCCS).
Scenario 3: Nuclear-based high temperature electrolysis (NHTE).
Scenario 4: Biomass gasification (BG).
Scenario 5: Hydropower-based water electrolysis (HWE).

The framework for prioritizing the different hydrogen production technologies using the proposed method was illustrated in Fig. 4. In this study, five hydrogen production technologies

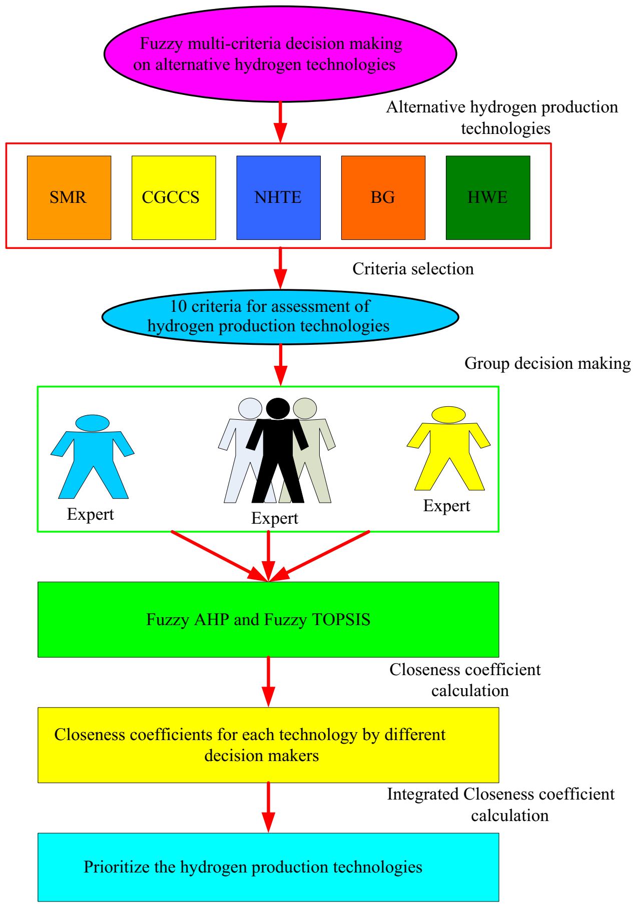

Fig. 4. Procedure of the group decision-making for prioritizing hydrogen production technologies by using the combined fuzzy AHP and fuzzy TOPSIS approach.

including SMR, CGCCS, NHTE, BG, and HWE were assessed and prioritized, and 10 criteria, i.e. technology maturity (C_1), technology reliability & stability (C_2), feedstock renewability (C_3), cost per unit of H_2 (C_4), market share (C_5), contribution to GDP (C_6), contribution to GHG mitigation (C_7), contribution to energy security (C_8), social acceptability (C_9), and degree of government support (C_{10}) were considered. Three groups of stakeholders/decision-makers, who are the representatives of hydrogen researchers, hydrogen producers, and hydrogen planners, respectively, have been invited to participate in the decision-making process. Among the three groups of representative participants, the hydrogen researchers (DM#1) consist of professors, senior researchers and Ph.D. students from several famous universities of China in the fields of renewable energy and hydrogen energy. The hydrogen producers (DM#2) are multiple engineers from different renewable energy companies and chemical factories. The hydrogen planners (DM#3) comprise a group of investors and administrative executors from the local government. A coordinator was nominated for each group to help the representatives to collect the opinions of the participants. The coordinator was responsible for organizing a colluquisium to achieve a consensus, in which, he/she was required to firstly propose a result according to the published papers, books, and technical reports, then inquire the experts to achieve a consensus according to their opinions.

4.2. Weight calculation

Fuzzy AHP was firstly used to determine the weight of each criterion, which is the prerequisite to prioritize various hydrogen production technologies by using fuzzy TOPSIS. The three groups of representative experts were asked to determine the comparison matrix regarding the four different assessment aspects, and the comparison matrices with respect to various criteria in each aspect (Table 3). It is notable that only one criterion (contribution to GHG mitigation) exists in the environmental aspect, therefore, the local weight of contribution to GHG mitigation with respect to the environmental aspect is 1.

Herein, the comparison matrix of the four aspects determined by DM#1 (Table 3) is selected as an example to illustrate the method of fuzzy AHP for the weight calculation, which were transformed into the fuzzy numbers in Table 4. Subsequently, the geometric mean of the fuzzy comparison value (GMFCV) of each aspect was calculated according to Eq. (10). For instance, GMFCV of the technical aspect (T) to other aspects is $[(1,1,1)\times(1/5,1/3,1)\times(1/9,1/7,1/5)\times(1/3,1,1)]^{1/4}=(0.29,0.47,0.67)$. By following the same procedure, the GMFCV of the other three aspects was also determined (Table 4). Then, the fuzzy weights of the four aspects could be calculated according to Eq. (11). For example, the weight of the technical aspect is

$$\frac{(0.29,0.47,0.67)}{(0.29,0.47,0.67)+(0.88,1.50,2.43)+(2.24,3.48,4.49)+(0.35,0.41,0.67)}$$

$$=(0.04,0.08,0.18).$$

Similarly, the local weights of the criteria in each aspect can also be calculated, and the overall weight of each criterion is the product of the weight of the corresponding aspect and the local weight of the criterion, the results are summarized in Table 5.

In order to investigate what the stakeholders/decision-makers care for, the fuzzy weights of the four aspects and the overall fuzzy weights of each criterion determined by each group of representative experts were defuzzied by the CoG method [65]. For instance, the fuzzy weight of the technical aspect determined by DM#1 is (0.04, 0.08, 0.18), it could be defuzzied by $(0.04+2\times0.08+0.18)/4=0.10$. Thus, its crisp weight is 0.10. The crisp weights of the four aspects and the crisp weights of each criterion obtained by defuzzying the fuzzy weights of the four aspects and the global weights of each criterion are presented in Figs. 5 and 6, respectively.

According to Fig. 5, it is apparent that all the representative experts hold the same view that economic and environmental priorities are the two main pillars in the assessment of hydrogen production technologies although DM#1 regarded that the environment aspect is the most important, whereas the economic aspect was regarded as the most preferred by both DM#2 and DM#3.

According to Fig. 6, the preference and willingness of the experts could be specified. DM#1 held the view that cost per unit of H_2 (C_4), market share (C_5) and contribution to GHG mitigation (C_7) are the top three concerns, and contribution to GHG mitigation is the most important criterion. DM#2 also considered that C_4, C_5, and C_7 are the top three concerns, but cost per unit of H_2 (C_4) is the most important criterion. Different form DM#1 and DM#2, DM#3 thought that C_5, C_6 and C_7 should be given the top priorities, and C_6 is the most important criterion.

It is reasonable that the weights determined by different group of experts are not same since the stakeholders/decision-makers from different groups have diverse preferences and willingness. This is just the reason that group decision-making is suggested in this study as hydrogen economy in China involves polytrophic interests.

4.3. Group decision-making on prioritizing hydrogen production technologies

In this section, fuzzy TOPSIS was used for prioritizing the five hydrogen production technologies, i.e. SMR, CGCCS, NHTE, BG and HWE. Firstly, the decision-making matrices were determined in

Table 3
The comparison matrices of the four aspects.

	DM#1					DM#2					DM#3			
	T	EC	EN	SP		T	EC	EN	SP		T	EC	EN	SP
T	1	LWE	LVS	LEQ	T	1	LVS	LEQ	EQ	T	1	LWE	LWE	WE
EC		1	LWE	ES	EC		1	ES	VS	EC		1	EQ	VS
EN			1	VS	EN			1	AB	EN			1	EQ
SP				1	SP				1	SP				1

	DM#1				DM#2				DM#3		
	C_1	C_2	C_3		C_1	C_2	C_3		C_1	C_2	C_3
C_1	1	EQ	VS	C_1	1	LWE	VS	C_1	1	LES	AB
C_2		1	VS	C_2		1	AB	C_2		1	AB
C_3			1	C_3			1	C_3			1

	DM#1				DM#2				DM#3		
	C_4	C_5	C_6		C_4	C_5	C_6		C_4	C_5	C_6
C_4	1	ES	ES	C_4	1	VS	VS	C_4	1	LES	LAB
C_5		1	VS	C_5		1	ES	C_5		1	LWE
C_6			1	C_6			1	C_6			1

	DM#1				DM#2				DM#3		
	C_8	C_9	C_{10}		C_8	C_9	C_{10}		C_8	C_9	C_{10}
C_8	1	VS	AB	C_8	1	WE	WE	C_8	1	LWE	LVS
C_9		1	WE	C_9		1	VS	C_9		1	LWE
C_{10}			1	C_{10}			1	C_{10}			1

Table 4
The comparison matrix of the four aspects and the corresponding parameters determined by DM#1 using fuzzy numbers.

	T	EC	EN	SP
T	(1,1,1)	(1/5, 1/3, 1)	(1/9, 1/7, 1/5)	(1/3,1,1)
EC	(1, 3 ,5)	(1,1,1)	(1/5, 1/3, 1)	(3,5,7)
EN	(5, 7, 9)	(1,3 ,5)	(1,1,1)	(5,7,9)
SP	(1, 1, 3)	(1/7, 1/5, 1/3)	(1/9, 1/7, 1/5)	(1,1,1)
GMFCV	(0.29, 0.47, 0.67)	(0.88, 1.50, 2.43)	(2.24, 3.48, 4.49)	(0.354, 0.41, 0.67)
Weights	(0.04, 0.08, 0.18)	(0.11, 0.26, 0.65)	(0.27, 0.59, 1.20)	(0.04, 0.07, 0.18)

Step 1 as described in Section 3.2.2. During the process, the representative experts were asked to assess the performance of the different hydrogen production technologies with respect to each criterion by using the linguistic variables presented in Table 6. Then, the linguistic variables were transformed into fuzzy numbers. The coordinator of each group was required to collect the views of the experts in the representative group to which he/she belongs, and then Delphi method [66,67] was used to achieve consistency in each group. Consequently, the performances of these hydrogen production technologies with respect to each criterion assessed by the three groups of representative decision-makers were determined. The results determined by DM#1 are presented in Table 7 as an example. Then, the decision-making matrices using fuzzy numbers determined by the three groups

Table 5
The weights of the four aspects, the local and overall weights of each criterion in each aspect determined by DM#1.

Aspect	Weight	Criterion	Local weight	Overall weight
Technical	(0.04, 0.08, 0.18)	C_1	(0.32, 0.47, 0.96)	(0.01, 0.04, 0.17)
		C_2	(0.22, 0.47, 0.67)	(0.01, 0.04, 0.12)
		C_3	(0.04, 0.07, 0.11)	(0.001, 0.01, 0.02)
Economic	(0.11, 0.26, 0.65)	C_4	(0.38, 0.67, 1.13)	(0.04, 0.17, 0.73)
		C_5	(0.16, 0.26, 0.45)	(0.02, 0.07, 0.29)
		C_6	(0.05, 0.07, 0.13)	(0.01, 0.02, 0.08)
Environmental	(0.27, 0.59, 1.20)	C_7	(1.00,1.00,1.00)	(0.27, 0.59, 1.20)
Social–political	(0.04, 0.07, 0.18)	C_8	(0.56, 0.79, 1.08)	(0.02, 0.06, 0.19)
		C_9	(0.08, 0.15, 0.25)	(0.003, 0.01, 0.05)
		C_{10}	(0.05, 0.07, 0.13)	(0.002, 0.005, 0.023)

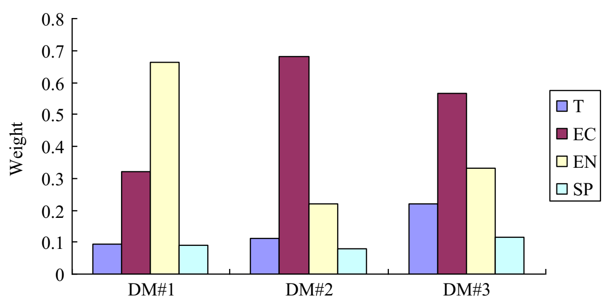

Fig. 5. Crisp weights of the four aspects determined by the three groups of representative decision-makers.

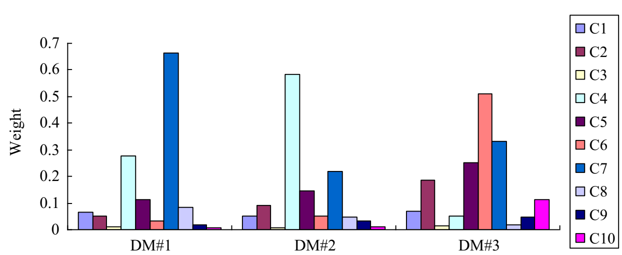

Fig. 6. Crisp weights of the criteria determined by the three groups of representative decision-makers.

Table 6
Linguistic variables used for evaluating the performance of hydrogen production technologies.

Linguistic variables	Abbreviation	Fuzzy number
Worst	WT	(0,1,1)
Worse	WE	(1,1,3)
Bad	BD	(1,3,5)
Medium	MM	(3,5,7)
Good	GD	(5,7,9)
Better	BR	(7,9,9)
Best	BT	(9,10,10)

of experts could also be obtained by transforming the linguistic terms into fuzzy numbers. For illustration, Table 8 listed the decision-making matrix using fuzzy numbers determined by DM#1.

Subsequently, according to the overall weights of the criteria and the fuzzy decision making matrices, fuzzy TOPSIS was used to rank the priority sequence of the five alternative technologies and the results are shown in Fig. 7. Finally, the integrated closeness coefficients of the five hydrogen production technologies are calculated as shown in Fig. 8.

According to the priority sequences ranked by the three groups of representative experts (Fig. 7), coal gasification with CO_2 capture and storage (CGCCS) was recognized as the most suitable hydrogen production technology for China by DM#1, followed by nuclear-based high temperature electrolysis (NHTE), hydropower-based water electrolysis (HWE), biomass gasification (BG), and steam methane reforming (SMR). While the priority sequences ranked by DM#2 and DM#3 are {HWE, CGCCS, NHTE, BG, SMR} and {CGCCS, HWE, SMR, NHTE, BG}, respectively. It is apparent that the priority sequences determined by the three groups are all different. Accordingly, group decision-making approach, which can incorporate the opinions of all the representative decision-

Table 7
The performances of various hydrogen production technologies with respect with each criterion evaluated by DM#1 with linguistic variables.

	SMR	CGCCS	NHTE	BG	HWE
C_1	BT	BR	GD	MM	BR
C_2	BR	BR	GD	MM	BT
C_3	BD	BD	BT	BT	BT
C_4	BR	BT	GD	GD	MM
C_5	GD	BT	GD	BD	BR
C_6	BR	BR	BT	BR	BT
C_7	MM	BT	BT	GD	BT
C_8	MM	MM	BT	BR	BT
C_9	GD	BR	BD	BT	BT
C_{10}	WT	MM	BR	BT	BR

Table 8
The performances of various hydrogen production technologies with respect to each criterion assessed by DM#1 using fuzzy numbers.

	SMR	CGCCS	NHTE	BG	HWE
C_1	(9,10,10)	(7,9,9)	(5,7,9)	(3,5,7)	(7,9,9)
C_2	(7,9,9)	(7,9,9)	(5,7,9)	(3,5,7)	(9,10,10)
C_3	(1,3,5)	(1,3,5)	(9,10,10)	(9,10,10)	(9,10,10)
C_4	(7,9,9)	(9,10,10)	(5,7,9)	(5,7,9)	(3,5,7)
C_5	(5,7,9)	(9,10,10)	(5,7,9)	(1,3,5)	(7,9,9)
C_6	(7,9,9)	(7,9,9)	(9,10,10)	(7,9,9)	(9,10,10)
C_7	(3,5,7)	(9,10,10)	(9,10,10)	(5,7,9)	(9,10,10)
C_8	(3,5,7)	(3,5,7)	(9,10,10)	(7,9,9)	(9,10,10)
C_9	(5,7,9)	(7,9,9)	(1,3,5)	(9,10,10)	(9,10,10)
C_{10}	(0,1,1)	(3,5,7)	(7,9,9)	(9,10,10)	(7,9,9)

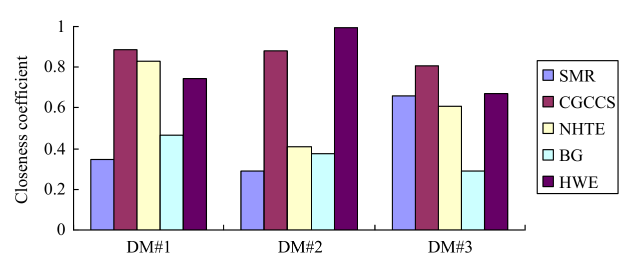

Fig. 7. Local closeness coefficients of the five hydrogen production technologies ranked by the three groups of representative decision-makers.

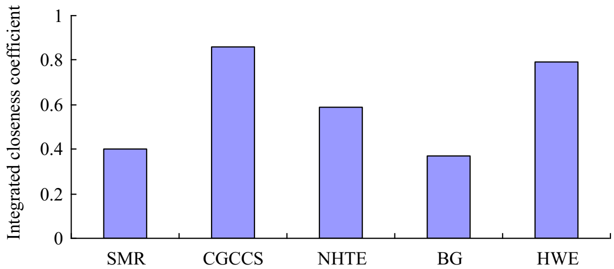

Fig. 8. Integrated closeness coefficients of the five hydrogen technologies.

makers, has to be used for determining the ultimate priority sequence.

According to the integrated closeness coefficients of the five hydrogen production technologies (Fig. 8), the final priority sequence by considering the integrated opinions of all the experts is {CGCCS, HWE, NHTE, SMR, BG}. The results are believed to be consistent with the current conditions of China. China is the third-largest coal reserve country in the world behind the United States and Russia [68]. Therefore, coal is predicted to play an important role in the future hydrogen economy of China because of its abundance and low market price [7]. Except the excellent economic performance of coal gasification technology for hydrogen production, the implement of CO_2 capture and storage makes the production of hydrogen by the coal gasification technology environment-friendly and also have high social acceptability. Therefore, it is reasonable that CGCCS is regarded as the most important and suitable technology. Similarly, China was the world's largest producer of hydroelectric power in 2010 with the electricity generation of 714 TWh [69]. HWE for hydrogen production is not only relatively cheap, but also environmental-friendly; its large potential dominates its role in the future hydrogen economy of China. It is notable that SMR was assessed to have low suitability for the hydrogen production in China, while it has been regarded as the most suitable for hydrogen production in Korea [70]. The main reason for this difference is the shortage and high price of natural gas in China [7]. The distribution of natural gas in China is highly uneven across the country and China also lacks the infrastructures such as long-distance pipelines for its transportation, which limits the consumption of natural gas in China [68]. Moreover, most of hydrogen from natural gas in China is used for ammonia and petroleum industries instead of the commercialization for hydrogen economy [68].

5. Discussion and conclusion

The transition to hydrogen economy is believed to be one of the best solutions for mitigating the severe problems in energy supply security and environmental contamination of China [71]. The prioritization of hydrogen production technologies is not only beneficial for planning the development of hydrogen economy in China, but also for allocating finite R&D budgets reasonably and scientifically. In order to help the stakeholders/decision to have a better understanding of the roles of different hydrogen production technologies in promoting the development of hydrogen economy in China, a multi-actor multi-criteria decision making methodology was proposed in this study.

An integrated DPSIR framework was firstly employed to identify the key criteria for the assessment of various hydrogen production technologies, in which, the cause–effect relationships in the development of hydrogen economy in China was analyzed and all the key factors were identified. Subsequently, the factors in "Drivers", "Pressures", "State", "Impact" and "Responses" were transformed into criteria that were categorized into economic, environmental, technical and social–political aspects, respectively.

Then, a group decision-making method by integrating fuzzy AHP and fuzzy TOPSIS was used to prioritize the hydrogen production technologies, in which, fuzzy AHP is used for calculating the weights of the criteria, and fuzzy TOPSIS is used to prioritize the hydrogen production technologies. The proposed decision-making method has several advantages: (1) it is capable of allowing multiple stakeholders/decision-makers to participate in the decision-making; (2) it is an object-oriented method that can identify the best scenario for the stakeholders/decision-makers according to their preferences/willingness and the actual conditions; and (3) linguistic variables are allowed to be used to evaluate the importance of the criteria and to assess the performances of the alternatives with respect to each criterion. Therefore, the method can address problems with uncertainty and imprecise information.

Five hydrogen production technologies i.e. steam methane reforming, coal gasification with CO_2 capture and storage, nuclear-based high temperature electrolysis, biomass gasification, and hydropower-based water electrolysis were assessed and prioritized by the proposed method. During the process, three groups of representative decision-makers were invited to participate in the decision-making. The results demonstrated that the weights with respect to the criteria and the priority sequences ranked by different groups are different due to their different preferences and willingness. Accordingly, the final priority sequence of the five hydrogen production technologies was determined by calculating the integrated closeness coefficients.

The overall priority sequence determined is CGCCS > HWE > NHTE > SMR > BG. CGCCS and HWE is predicted to play an important role in the future hydrogen economy of China for the abundance and low cost of their feedstock and good environmental performance of the technologies, which fits well with the current conditions of China.

Finally, several points are noteworthy about this study. (1) The prioritization is based on the current conditions of China and also the preferences of the participants. With the development of hydrogen technologies, the result is up to change. (2) The prioritization is based on the views of the decision-makers, and thus, the accuracy of the results can be benefited through wilder public perceptions. (3) The aim of this study is to propose a modular approach for prioritizing the role of different hydrogen production technologies in promoting the development of hydrogen economy in China according to the current conditions of China, and thus, five hydrogen production pathways have been selected to illustrate the proposed methodology. The stakeholders/decision-makers can add more pathways according to their preferences and China's future conditions in the followed studies. (4) The proposed group decision-making method is object-oriented that is not limited to China and could be popularized to other regions.

A further work that can assess the whole hydrogen infrastructures including hydrogen production technologies, hydrogen storage & transportation and hydrogen applications is a natural extension of this study; the authors is planning to develop a novel multi-actors multi-criteria decision-making method for ranking the priority sequence of hydrogen infrastructures in China.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.09.028.

References

[1] Feng W, Wang S, Ni W, Chen C. The future of hydrogen infrastructure for fuel cell vehicles in China and a case of application in Beijing. Int J Hydrogen Energy 2004;29(4):355–67.

[2] Shaw L, Pratt J, Klebanoff L, Johnson T, Arienti M, Moreno M. Analysis of H_2 storage needs for early market man-portable fuel cell applications. Int J Hydrogen Energy 2013;38:2810–23.

[3] Mansilla C, Avril S, Imbach J, Duigou AL. CO_2-free hydrogen as a substitute to fossil fuels: what are the targets? Perspective assessment of the hydrogen market attractiveness Int J Hydrogen Energy 2012;37:9451–8.

[4] Yao F, Jai Y, Mao Z. The cost analysis of hydrogen life cycle in China. Int J Hydrogen Energy 2010;35:2727–31.

[5] Markets and Markets consulting firm. Hydrogen generation market. File available: 〈http://www.marketsandmarkets.com/Market-Reports/hydrogen-generation-market-494.html〉.

[6] Ma T, Ji J, Chen MQ. Study on the hydrogen demand in China based on system dynamics model. Int J Hydrogen Energy 2010;35(7):3114–9.

[7] Deng X, Wang H, Huang H, Ouyang M. Hydrogen flow chart in China. Int J Hydrogen Energy 2010;35:6475–81.

[8] Zhao J, Melaina MW. Transition to hydrogen-based transportation in China: lessons learned from alternative fuel vehicle programs in the United States and China. Energy Policy 2006;34:1299–309.

[9] Moreno J, Dufour J. Life cycle assessment of hydrogen production from biomass gasification. Evaluation of different feeddstocks. Int J Hydrogen Energy 2013;38:7616–22.

[10] Parker NC, Ogden JM, Fan Y. The role of biomass in California's hydrogen economy. Energy Policy 2008;36:3925–39.

[11] Cohce MK, Dincer II, Rosen MAMA. Thermodynamic analysis of hydrogen production from biomass gasification. Int J Hydrogen Energy 2010;35: 4970–4980.

[12] Kalinci Y, Hepbasli A, Dincer I. Life cycle assessment of hydrogen production from biomass gasification systems. Int J Hydrogen Energy 2012;37:14026–39.

[13] Abuadala A, Dincer I. A review on biomass-based hydrogen production and potential applications. Int J Energy Res 2012;36:415–55.

[14] Luk HT, Lei HM, Ng WY, Ju Y, Lam KF. Techno-economic analysis of distribution hydrogen production from natural gas. Chin J Chem Eng 2012;20:489–96.

[15] Simpson AP, Lutz AE. Exergy analysis of hydrogen production via steam methane reforming. Int J Hydrogen Energy 2007;32:4811–20.

[16] Boyano A, Blanco-Marigorta AM, Morosuk T, Tsatsaronis G. Exergoenvironmental analysis of a stream methane reforming process for hydrogen production. Energy 2011;36:2202–14.

[17] Stiegel GJ, Ranezan M. Hydrogen from coal gasification: an economical pathway to a sustainable energy future. Int J Coal Geol 2006;65:173–90.

[18] Jin H, Lu Y, Laio B, Guo L, Zhang X. Hydrogen production by coal gasification in supercritical water with a fluidized bed reactor. Int J Hydrogen Energy 2010;35:7151–60.

[19] Gnanapragasam NV, Reddy BV, Rosen MA. Hydrogen production from coal gasification from effective downstream CO_2 capture. Int J Hydrogen Energy 2010;35:4933–43.

[20] Cormos CC, Starr F, Tzimas E, Peteves S. Innovative concepts for hydrogen production processes based on coal gasification with CO_2 capture. Int J Hydrogen Energy 2008;33:1286–94.

[21] Sinha P, Pandey A. An evaluative report and challenges for fermentative biohydrogen production. Int J Hydrogen Energy 2011;36:7460–78.

[22] Yuan X, Shi X, Zhang P, Wei Y, Guo R, Wang L. Anaerobic biohydrogen production from wheat stalk by mixed microflora: kinetic model and aprticle size influence. Bioresour Technol 2011;102:9007–12.

[23] Kovacs KL, Maroti G, Rakhely G. A novel approach for biohydrogen production. Int J Hydrogen Energy 2006;31:1460–8.

[24] Lee JY, An S, Cha K, Hur T. Life cycle environmental and economic analyses of a hydrogen station with wind energy. Int J Hydrogen Energy 2010;35:2213–25.

[25] Menanteau PP, Quemere MMMM, Duigou ALAL, Bastard SLSL. An economic analysis of the production of hydrogen from wind generated electricity for use in transport applications. Energy Poliy 2011;39:2957–65.

[26] Khamis I. An overview of the IAEA HEEP software and international programmes on hydrogen production using nuclear energy. Int J Hydrogen Energy 2011;36:4125–9.

[27] Graf D, Monnerie N, Roeb M, Schmitz M, Sattler C. Economic comparison of solar hydrogen generation by means of thermochemical cycles and electrolysis. Int J Hydrogen Energy 2008;33:4511–9.

[28] Lu Y, Zhao L, Guo L. Technical and economic evaluation of solar hydrogen production by supercritical water gasification of biomass in China. Int J Hydrogen Energy 2011;36:14349–59.

[29] Bozoglan E, Midilli A, Hepbasli A. Sustainable assessment of solar hydrogen production techniques. Energy 2012;46:85–93.

[30] Liu Z, Qiu Z, Luo Y, Mao Z, Wang C. Operation of first solar-hydrogen system in China. Int J Hydrogen Energy 2010;35(7):2762–6.

[31] Han WW, Zhang GG, Xiao JJ, Bénard PP, Chahine R. Demonstrations and marketing strategies of hydrogen fuel cell vehicles in China. Int J Hydrogen Energy 2014;3(25):13859–72.

[32] Lv P, Wu C, Ma L, Yuan Z. A study on the economic efficiency of hydrogen production from biomass residues in China. Renew Energy 2008;33(8): 1874–9.

[33] Ren J, Fedele A, Mason M, Manzardo A, Scipioni A. Fuzzy multi-actor multi-criteria decision making for sustainability assessment of biomass-based technologies for hydrogen production. Int J Hydrogen Energy 2013;38: 9111–20.

[34] Manzardo A, Ren J, Mazzi A, Scipioni A. A grey-beased group decision-making methodology for the selection of hydrogen technologies in life cycle sustianability perspective. Int J Hydrogen Energy 2012;37:17663–70.

[35] McDowall W, Eames M. Towards a sustainable hydrogen economy: a multi-criteria sustainability appraisal of competing hydrogen futures. Int J Hydorgen Energy 2007;32:4611–26.

[36] Pilvachi PA, Chatzipanagi AI, Spyropoulou AI. Evaluation of hydrogen production methods using the analytic hierarchy process. Int J Hydrogen Energy 2009;34:5294–303.

[37] Heo E, Kim J, Cho S. Selecting hydrogen production methods using fuzzy analytic hierarchy process with opportunities, costs and risks. Int J Hydrogen Energy 2012;37:17655–62.

[38] Lee S, Mogi G, Lee S, Kim J. Prioritizing the weights of hydrogen energy technologies in the sector of the hydrogen economy by using a fuzzy AHP approach. Int J Hydrogen Energy 2011;36:1897–902.

[39] Chang PL, Hsu CW, Chang PC. Fuzzy Delphi method for evaluating hydrogen production technologies. Int J Hydrogen Energy 2011;36:14172–9.

[40] Lee S, Mogi G, Li Z, Hui KS, Lee SK, Hui KN, et al. Measuring the relative efficiency of hydrogen energy technologies for implementing the hydrogen economy: an integrated fuzzy AHP/DEA approach. Int J Hydrogen Energy 2011;36:12655–63.

[41] Wang JJ, Jing YY, Zhang CF, Zhao JH. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew Sustain Energy Rev 2009:2263–78.

[42] Kahraman C, Kaya I, Cebi S. A comparative analysis for multiattribute selection among renewable energy alternatives using axiomatic design and fuzzy analytic hierarchy process. Energy 2009;34:1603–16.

[43] Kara T, Kahraman C. Multi-criteria decision making in energy planning using a modified fuzzt TOPSIS methodology. Expert Syst Appl 2011;38:6577–85.

[44] Dagdeviren M, Yavuz S, Kilinc N. Weapon selection using the AHP and TOPSIS methods under fuzzy environment. Expert Syst Appl 2009;36:8143–51.

[45] Saaty TL. Multicriteria decision making: the analytic hierarchy process. New York: McGraw-Hill; 1980.

[46] Cables E, Cascales MSG, Lamata MT. The LTOPSIS: an alternative to TOPSIS decision-making approach for linguistic variables. Expert Syst Appl 2012;39: 2119–26.

[47] Krohling RA, Campanharo V. Fuzzy TOPSIS for group decision making: a case study for accidents with oil spill in the sea. Expert Syst Appl 2011;38:4190–7.

[48] Cavallaro F. Fuzzy TOPSIS approach for assessing thermal-energy storage in concentrated solar power (CSP) systems. Appl Energy 2010;87:496–503.

[49] Torfi F, Farahani RZ, Rezapour S. Fuzzy AHP to determine the relative weights of evaluation criteria and Fuzzy TOPSIS to rank the alternatives. Appl Soft Comput 2010;10:520–8.

[50] Wang Q. China needing a cautious approach to nuclear power strategy. Energy Policy 2009;37:2487–91.

[51] Shih HS, Shyur HJ, Lee ES. An extension of TOPSIS for group decision making. Math Comput Model 2007;45:801–13.

[52] Huang HF, Kuo J, Lo SL. Review of PSR framework and development of a DPSIR model to assess greenhouse effect in Taiwan. Environ Monit Assess 2011;177: 623–35.

[53] European Environment Agency (EEA). Environmental indicators: typology and overview: technical report No. 25. Copenhagen: European Environment Agency.

[54] OECD. OECD core set of indicators for environmental performance review. OECD Environmental Directorate Monographs No. 83. Organisation of Economic Co-operation and Development; 1993.

[55] UN. United Nations Indicators of sustainable development. Framework and methodologies. Report; 1996.

[56] OECD. Environmental indicators-development measurement and use. Report. Organisation of Economic Co-operation and Development; 2003.

[57] Kim Y, Chung ES, Jun SM, Kim SU. Prioritizing the best sites for treated waste instream use in an urban watershed using fuzzy TOPSIS. Resour Conserv Recycl 2013;73:23–32.

[58] Chung ES, Lee KS. Prioritization of water management for sustainability using hydrologic simulation model and multicriteria decision making techniques. J Environ Manag 2009;90:1502–11.

[59] Jun KS, Chung ES, Sung JY, Lee KS. Development of spatial water resources vulnerability index considering climate change impacts. Sci Total Environ 2011;409:5228–42.

[60] Zhang B, Deng W. Indicators for transportation network in economic circle based on DPSIR model. J East China Jiaotong Univ 2011;28(4):7–13 (in Chinese).

[61] Maxim L, Spangenberg JH, O'Connor M. An analysis for biodiversity under the DPSIR framework. Ecol Econ 2009;69:12–23.

[62] Hsieh TY, Lu ST, Tzeng GH. Fuzzy MCDM approach for planning and design tenders selection in public office buildings. Int J Proj Manag 2004;22:573–84.

[63] Wang JJ, Jing YY, Zhang CF, Shi GH, Zhang XT. A fuzzy multi-criteria decision-making model for trigeneration system. Energy Policy 2009;36:3823–32.
[64] Wang J, Cheng CH, Cheng HK. Fuzzy hierarchy TOPSIS for supplier selection. Appl Soft Comput 2009;9:377–86.
[65] Stylios CD, Georgopoulos VC, Malandraki GA, Chouliara S. Fuzzy cognitive map architectures for medical decision support systems. Appl Soft Comput 2008;8:1243–51.
[66] Sharma DP, Nair PSC, Balasubramanian R. Analytical search of problems and prospects of power sector through Delphi study: case of Kerala State, India. Energy Policy 2003;31:1245–55.
[67] Makkonen M, Patari S, Jantunen A, Viljainen S. Competition in the European electricity markets-outcomes of a Delphi study. Energy Policy 2012;44:431–40.
[68] Lu J, Zahedi A, Yang C, Wang M, Peng B. Building the hydrogen economy in China: drivers, resources and technologies. Renew Sustain Energy Rev 2013;23:543–56.
[69] EIA. China energy profile: increasing demand makes China influential on world markets-Analysis. It is available at: ⟨http://www.eurasiareview.com/05092012-china-energy-profile-increasing-demand-makes-china-influential-on-world-markets-analysis/⟩.
[70] Heo E, Kim J, Cho S. Selecting hydrogen production methods using fuzzy analytic hierarchy process with opportunities, costs, and risks. Int J Hydrogen Energy 2012;37:17655–62.
[71] Yuan K, Lin W. Hydrogen in China: policy, program and progress. Int J Hydrogen Energy 2010;35:3110–3.